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**Laser technology impact on the ITRS wafer defect inspection roadmap**

## *Introduction*

Semiconductor device dimensions and corresponding defect dimensions continue shrinking, posing increasing challenges to detection. Development of defect detection, defect review, and classification technologies delivering high sensitivity at high throughput is crucial for cost efficient manufacturing. The ability to detect in-line yield-limiting defects on specific process layers is the primary requirement of wafer defect detection technology. The detection of multiple defect types and simultaneous differentiation at high capture rates, low cost of ownership, and high throughput continues to be a critical challenge for the semiconductor industry.

Currently, inspection systems are expected to detect defects with sizes scaling down in the same way or even faster as feature sizes defined by technology generations. Existing techniques trade-off throughput for sensitivity, but at current defect levels, both throughput and sensitivity are necessary for statistical validity.

In addition, the need for higher sensitivity of in-line inspections is leading to a dramatic increase in defect counts. It is a challenge to find small but relevant defects under a vast amount of nuisance and false defects. At the same time, a low Cost of Ownership (CoO) target for the tools demands high throughput of the inspection. The competing objectives of high sensitivity, high signal-to-noise and low CoO have resulted in a lack of technical solutions and roadmap for both unpatterned and patterned wafer defect inspection at the 45nm node.

*Table YE6a Defect Inspection on Pattern Wafer Technology Requirements—Near-term Years*

| *Year of Production* | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|---|---|---|
| *DRAM ½ Pitch (nm) (contacted)* | 65 | 57 | 50 | 45 | 40 | 35 | 32 | 28 | 25 |
| *Flash ½ Pitch (nm) (un-contacted Poly)(f)* | 54 | 45 | 40 | 36 | 32 | 28 | 25 | 22 | 20 |
| *Patterned Wafer Inspection, PSL Spheres * at 90% Capture, Equivalent Sensitivity (nm) [A, B]* | | | | | | | | | |
| Process R&D at 300 cm²/hr (0,4 "300 mm wafer"/hr) | 27 | 22.5 | 20 | 18 | 18 | 14 | 12.5 | 11 | 10 |
| Process R&D at 300 cm2/hr with 50 % Capture rate [Q] | 16.2 | 13.5 | 12 | 10.8 | 8.8 | 8.4 | 7.5 | 6.8 | 6 |
| Yield ramp at 1200 cm²/hr (1,7 "300 mm wafer"/hr) | 43.2 | 38 | 32 | 28.8 | 25.8 | 22.4 | 20 | 17.6 | 16 |
| Volume production at 3000 cm²/hr (4,3 "300 mm wafer"/hr) | 54 | 45 | 40 | 38 | 32 | 28 | 25 | 22 | 20 |
| Speed [wafer/hrs]at volume production (1xDR) on Brigthfield tools [R] | 4 | 4 | 6 | 6 | 6 | 6 | 6 | 6 | 7 |
| Tool matching (% variation tool to tool) [C] | 10 | 10 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Defect coordinate precision [µm] note | 2.276 | 1.995 | 1.75 | 1.575 | 1.4 | 1.225 | 1.12 | 0.88 | 0.875 |
| Defect coordinate precision [µm] note | 1.89 | 1.575 | 1.4 | 1.28 | 1.12 | 0.98 | 0.875 | 0.77 | 0.7 |
| Wafer edge exclusion (mm) | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Cost of ownership ($/cm²) | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 | 0.08 |
| *E-beam inspection Inspection: Defects other than Residue, Equivalent Sensitivity in PSL Diameter (nm) at 90% Capture Rate *[D, E]* | | | | | | | | | |
| Sensitivity for voltage contrast application without speed requirement (nm) | 65 | 57 | 50 | 45 | 40 | 35 | 32 | 28 | 25 |
| Sensitivity for physical defect detection (nm) | 27 | 22.5 | 20 | 18 | 18 | 14 | 12.5 | 11 | 10 |
| speed for voltage contrast applications | 50 | 100 | 100 | 100 | 300 | 300 | 300 | 300 | 500 |
| Speed for physical defect detection | 10 | 50 | 50 | 50 | 50 | 50 | 50 | 100 | 100 |
| CoO HARI ($/cm²) | 0.388 | 0.388 | 0.388 | 0.388 | 0.388 | 0.388 | 0.388 | 0.388 | 0.388 |
| *Backside cleaniness for inspection tools* | | | | | | | | | |
| Critical Defect Size (µm) for large defects | 50 | 20 | 20 | 20 | 10 | 10 | 10 | 10 | 10 |
| Backside Particle per Wafer pass (PWP) Budget (defects/m²) for large defects | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| Critical Defect Size (nm) for total defects | 325 | 285 | 250 | 225 | 200 | 175 | 160 | 140 | 125 |
| Backside Particle per Wafer pass (PWP) Budget (defects/m²) for total defects | 3500 | 2500 | 2500 | 2500 | 2500 | 2500 | 2500 | 2500 | 2500 |

*Manufacturable solutions exist, and are being optimized*
*Manufacturable solutions are known*
*Interim solutions are known*
*Manufacturable solutions are NOT known*

**SEMI 2007 ITRS Roadmap**

### *Industry Roadmap*

As a direct result of Moore's Law and aggressive design rule shrinks that characterize the semiconductor industry, defect sensitivity at throughput requirements have exceeded the available manufacturable solutions. Current best-of-breed solutions utilize either low power deep ultraviolet lasers (248nm-266nm) or high power solid-state ultraviolet lasers (355nm). The lack of manufacturable solutions to achieve the ITRS roadmap objectives is a direct result of limitations associated with existing deep ultraviolet (DUV) laser technology. Current DUV lasers are limited by optical characteristics of the materials utilized to achieve the DUV wavelength at high output power. Traditional optical materials have mechanical, environmental and optical deficiencies which limit their effective output power at DUV wavelengths to a few hundred milliwatts. Today's best-of-breed defect inspection systems, which utilize 248nm lasers at ~500mW, are capable of achieving 40nm defect detection with 90% capture rate at 3000 cm²/hr, with a CoO of $0.08/cm². The ITRS roadmap

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identifies a ~12% year-over-year improvement in sensitivity at comparable throughput and CoO. Clearly, an economical solution to higher defect sensitivity is required.

### *Wafer Inspection Physics*

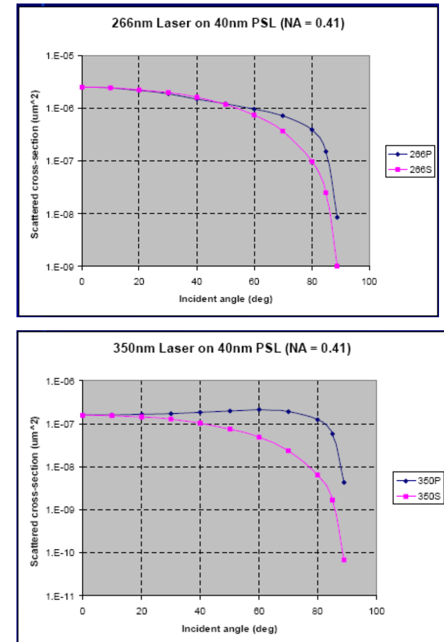
The detection of defects and their classification is achieved with wafer inspection technology. Wafer inspection is performed by scanning one or more focused laser spots over the test surface. Wafers are highly reflective, resulting in the capture of both reflected and scattered light. When patterned wafers are illuminated, laser light is scattered by defects, the pattern itself, as well as by rough or grainy surfaces. The amount of laser light scattered, and therefore the sensitivity of the detection, is described by the Rayleigh scattering equation. This relationship defines the relative contribution of incident intensity and wavelength, to sensitivity, for a given optical defect inspection system. Because the sensitivity increases as the fourth power of the incident wavelength, virtually all wafer defect inspection equipment suppliers have focused on reducing the incident laser wavelength as the primary strategy for achieving industry sensitivity and CoO targets. Alternatively, sensitivity also scales linearly with the incident power. This also gives a straight forward approach to increase the sensitivity by increasing the output power of the laser source.

$$Is = \frac{\pi^4 r^6}{8 d^2 \lambda^4} \left| \frac{n^2-1}{n^2+2} \right|^2 (1 + \cos^2\theta)\ Ii$$

**Is : Scattered light intensity**
**Ii : Incident light intensity**
**r : Particle diameter**
**λ : Wave length**
**θ : Angle of the incident list**
**d : Distance from the particle**

### *Laser Wavelength Selection*

There has been an inordinate amount of work and data collected by innumerable public and private organizations on the relationship between laser wavelength and wafer defect sensitivity. Because the ITRS roadmap specifies a specific test methodology, we have chosen to use the definitive work performed on the NIST Multidetector Hemispherical Polarized Optical Scattering Instrument (MHPOSI) and published by NIST on the subject, to illustrate the benefits of DUV wavelengths. The pertinent data compares defect sensitivity measured with 40nm PSL spheres on smooth Silicon substrate illuminated with three wavelengths (532nm, 350nm, and 266nm), P and S polarization, and various incident angles. The experimental results clearly identify the expected increase in sensitivity, by a factor of >10, between 266nm and 350nm; and a factor of >200 between 266nm and 532nm. The high degree of sensitivity improvement between DUV 266nm, UV 350nm and visible 532nm makes it imperative to utilize DUV wavelengths in future defect inspection systems to achieve the ITRS targets.




### *Laser Technologies*

Virtually all lasers used to achieve DUV wavelengths for wafer defect detection use a technique known as frequency conversion. Frequency conversion is accomplished by passing laser light at a fundamental wavelength, through a non-linear optically active crystal (NLO). Specific crystalline attributes of the NLO material cause the fundamental wavelength to be converted to half of its original wavelength; this process is known as second harmonic generation (SHG). This general technique can be used to produce additional harmonics

including the third harmonic (THG), the fourth harmonic (FHG) and the fifth harmonic (SFG). Most solid-state lasers used today in wafer inspection utilize a fundamental wavelength of 1064nm, resulting in a SHG wavelength of 532nm, a THG wavelength of 355nm, a FHG wavelength of 266nm and a SFG wavelength of 213nm.

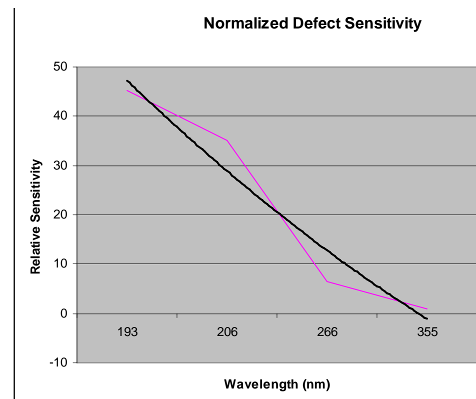
In addition, laser designs come in two operating modes, continuous wave (CW) and pulsed. CW lasers emit a constant amplitude laser output. Pulsed laser designs emit a time varying amplitude laser output. The rate of the amplitude variance in pulsed designs is defined as the pulse frequency. When the pulse frequency is sufficiently high relative to the detection bandwidth of the wafer defect inspection system sensor electronics, the laser effectively appears as a quasi continuous source, or qCW. For the majority of wafer defect inspection systems, qCW laser designs with pulse frequencies greater than 100 MHz deliver comparable results to a CW design.

Solid-state DUV qCW lasers are characterized by the use of temporally short (~10ps), high intensity (>1kW), high frequency (>100MHz) pulses which pass through multiple stages of frequency conversion in a single pass. The desire for high intensity pulses is due to the non-linear nature of the frequency conversion process. The efficiency of the process is proportional to the square of the intensity of the incoming laser light. The practical limit for the number of frequency conversion stages is dictated by the maximum conversion capability, in the DUV, of the NLO crystal employed. Achieving high power FHG at 266nm and SFG at 213nm with a qCW laser strictly becomes a question of the capability of the NLO.

In contrast to CW limitations, qCW designs have virtually no sensitivity to typical environmental conditions. In addition, absorption is a secondary concern; in fact most high intensity qCW systems abandon the use of anti-reflection coatings on the DUV NLO crystals to improve component lifetime. The most striking comparison with CW systems is the advantage of using picosecond pulses. Virtually all NLO's, possess a remarkable attribute in where the damage threshold of the material increases as the inverse square root of the pulse duration. For example, if a specific material has a damage threshold of of 1GW/cm² at a pulse duration of 10ns, then the damage threshold at 10ps is 31 times higher, or 31GW/cm². This attribute, coupled with the square intensity law efficiency nature of the frequency conversion process, provides an overwhelming incentive to adopt short pulse, high intensity, high frequency laser designs as the preferred technical direction to achieve high power DUV laser sources.

### *Roadmap Implications*

Anticipating the substantial DUV laser technology barrier, Deep Photonics has developed a DUV qCW fiber laser based on a new class of optically active non-linear materials. This material enables high power, solid-state lasers with a DUV wavelength at 266nm, improving detection sensitivity by 100% compared to currently available 248nm argon lasers. The attributes of the material also provide a technical roadmap to 213nm and 206nm, eventually generating sensitivity gains of 2500% compared with current technology. With Deep Photonic's product offering, wafer defect inspection system suppliers can more than double their sensitivity, meeting or exceeding the ITRS roadmap sensitivity requirements until 2020. This technical runway provides an attractive opportunity for



suppliers to utilize the advantages of Deep Photonic's technology to drive significant improvement in CoO reduction through improved throughput.

### *Conclusion*

The semiconductor industry requires continuing improvement in sensitivity and throughput for both patterned and unpatterned wafer defect inspection. To achieve these goals, wafer defect inspection systems will likely employ frequency converted, solid-state lasers with lower wavelength and higher power than they currently utilize. High peak power, picosecond pulses from a high frequency, mode-locked fiber laser can be frequency converted through multiple stages of wavelength conversion based on new NLO material. This technique provides a direct roadmap to wafer defect inspection using high power 266nm, 213nm and 206nm solid-state lasers with low technical risk.

### *Ackowledgements*

### *References*